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INTRODUCTION

Interest in adaptive flight control systems arose out of difficulties encountered or foreseen with the use of fixed-gain flight control systems in high-speed aircraft. The characteristics of these aircraft vary so greatly that the gain of the self-adaptive system would have to be constantly changed in flight to achieve the desired results. Gain scheduling had fallen into disfavor primarily for three reasons: (1) because of the extensive amount of aerodynamic information that was required but not always available; (2) because of the lengthy development time necessary to establish the best gain settings; and (3) because the process might have to be repeated for a subsequent airplane configuration change. Thus, an alternate approach was sought--a flight control system that contained the logic which would enable the "best" gain to be chosen automatically and would not require a complete set of aircraft characteristics.

In 1955, the Flight Control Laboratory of the Wright Air Development Division initiated a program to develop new techniques in flight control systems. Contracts were let to several companies to develop a variety of "self-adaptive" flight control systems. It was then decided that a manned space vehicle provided the conditions that were particularly well suited to a self-adaptive system. Honeywell was given the task of assessing the performance of the various systems concepts with regard to such a vehicle in general and to the X-15 in particular. At the completion of this study, the self-adaptive technique was shown to have sufficient promise that a contract was awarded to develop and flight test a system in the X-15. The results of the study indicated that, because rapid gain changes were necessary, the best gain-changing concept was proposed by Honeywell. With this concept, the forward-loop gain in each axis is kept critical by monitoring the activity of the system output in the frequency range at which the system becomes unstable. In simple terms, activity greater than a set amount is interpreted as excessively high gain; consequently, the gain is lowered. Conversely, if the activity is less than the set amount, the gain is increased. In this way, the gain of each axis would be kept at a maximum value consistent with system stability over a large range of vehicle dynamics. This concept seemed to have great promise, and many advantages were advanced by its proponents, such as:

Total development and flight-test time would be reduced from that which previous systems required.

External data scheduling could be eliminated.

A nearly invariant response to control command, regardless of flight condition or varying vehicle characteristics, could be achieved with a minimum of information about the primary control system.

Some disadvantages were also expected:

The system would be more than just a damper; it was going to be a very complex autopilot and this complexity was not expected to help reliability.

Because of the high gain loop, the servos would be very active and have a shortened service life.

The system performance might deteriorate if noise or rapid pilot inputs drove the gains to low values.

Structural coupling problems might occur at high gains.

This paper discusses the development and operation of this adaptive control system and indicates which goals were met and which were not. In addition, what an adaptive system offers when subjected to the constraints of actual hardware is considered briefly.

X-15 AIRPLANE

The X-15 research airplane (fig. 1) is launched from a B-52 and powered by a rocket engine to speeds up to Mach 6 or to altitudes of 350,000 feet. The basic control system is standard in that the pilot input is summed mechanically with the (SAS) servo input which then, through irreversible power actuators, positions the upper and lower rudders and right and left horizontal stabilizers. The horizontal surfaces provide both longitudinal and lateral control. Control moment at the higher altitudes is provided by duplicate sets of hydrogen-peroxide rockets mounted in the nose and the wing tips. The pilot can manually fire the rockets through a special control provided at the left of the cockpit, or he can allow the reaction augmentation system to provide damping.

ADAPTIVE CONTROL SYSTEM

The adaptive control system was to be much more than another SAS with a variable gain changer. Its major features were to be as follows:

Model response would be incorporated and rate command control in pitch and roll would be provided.

Pilot input in both aerodynamic and ballistic portions of flight would be made through the same controller, with the reaction controls to be engaged automatically.

Automatic longitudinal trim would be provided.

Angle of attack, angle of pitch, and bank angle and/or heading hold modes would be available to enable hands-off flight.

Automatic limiting of normal acceleration would be used to make entries from high altitude easier.

Fail operational capability and high reliability was to be provided.

A greatly simplified block diagram of the system is shown in figure 2. This diagram is for only the pitch axis but is typical of the roll and yaw axes. First, note that the mechanical connection linking the pilot's control stick with the surface actuators has not been altered, so that control of the unaugmented airplane is unchanged. Next, note that for the high-gain portion of the system the pilot input is shaped by the model to give the desired response, which is compared with the actual response given by the rate gyro. This difference is then driven to zero by the tight control loop provided by the high forward-loop gain.

The gain changer discussed previously is shown in figure 2. The servo feedback signal is band-passed, rectified, and compared with a set point. The sign of this difference then drives the gain up if the servo motion is less than the set point and down if the servo activity is greater than the set point.

In addition to the signal paths shown in the figure, there are paths which contain only passive electronics, except for the summing and servo amplifiers, to provide a highly reliable constant-gain channel in the event of a complete failure in the adaptive portion of the system.

Automatic trim follow-up is required in the system because the authority of the SAS servos is only a fraction of that of the control surfaces in pitch. This is provided by operating the trim motor when the SAS servos exceed 20 percent of the total servo travel.

The circuitry which provides control through the reaction controls is not shown in the simplified block diagram (fig. 2). An idea of what makes up the X-15 adaptive flight control system can be obtained by doubling the circuitry to show the dual channels of each axis, adding the roll and yaw axes, the pitch, roll and heading hold modes, monitors, and a g-limiter.

DEVELOPMENTAL EXPERIENCE

Although considerable study and experience had gone into the design of the X-15 adaptive flight control system in the form of analog-computer studies and F-101A flight-test experience with a system with the same concepts, several problems were encountered when a breadboard of the adaptive flight control system was hooked up to the X-15 flight simulator (fig 3). The simulator consists of a full-size operating mockup of the complete control system: cockpit, control sticks, cables, linkages, servo actuators, power actuators, and mock control surfaces. Complete six-degree-of-freedom motion is computed with an analog-computer complex which enables complete missions to be "flown" from launch to landing. When the actual hardware was used, the first difficulties were uncovered.

The hysteresis or lost motion in the X-15 control system was large compared to that of the F-101A and presented a problem particularly during entry maneuvers from high altitudes. At high altitude the gains would, of course, be driven to their maximum values in trying to compensate for the almost zero aerodynamic-control effectiveness. During entry, the aerodynamic-control effectiveness builds up beyond the point for critical gain, but, because of the lost motion, the loop is not closed until a disturbance exceeds the hysteresis. Considerable motion of the pilot's controls resulted from these excessive gains, because the servos moved so rapidly that the surface actuators could not keep up. The action

was passed upstream to the pilot. This problem also occurred, to a lesser extent, at other flight conditions when, because of the lack of motion, the gains would drift to supercritical values and cause a brief period of shaking when the motion would exceed the hysteresis. By putting flow restrictors in the servo actuators to make their maximum rate of operation more consistent with that of the surface actuators, shaking of the pilot's controls was eliminated. Also, the dynamics of the gain computer was changed so that the gain was rapidly reduced to a subcritical value before shaking could develop.

On the other side of the coin was the problem of keeping the gain up to a near-critical value when pilot inputs tend to drive the gain down momentarily. This problem was most apparent in ballistic flight because the gain values were used to automatically engage the reaction controls. At altitude, while relying on reaction controls, a sharp pilot input could drive the gain low enough to disengage the reaction controls until the gain worked its way back up. This problem was eliminated by adding a high-pass filter and limiter to the servo signal used by the gain computer. In this way, the effect of the low-frequency but large-amplitude pilot inputs was greatly reduced without affecting the small-amplitude high-frequency signal necessary for proper gain adjustment. In addition, the reaction-control-engage logic was changed to allow for small dips in the gain values to prevent premature disengagement of the reaction controls.

During simulated flights, the pilots expressed a desire for faster pitch response than provided by the second-order model with a natural frequency of 2 radians per second. Consequently, the model dynamics was made to be of first order. This action points out that the airplane response did not always follow the model exactly or, if it did, a second-order response was not necessarily best for a rate command system.

Operation of the automatic trim system presented a problem, particularly at high altitude, by slowly oscillating, thus causing the control stick to wander. This problem was alleviated by reducing the rate at which the trim actuator functioned, thereby reducing the gain of that particular loop.

It should be emphasized that all of these problems were encountered and corrected before the flight article existed, by virtue of the extensive and realistic simulation possible with the X-15 flight simulator.

Very late in the development of the system, a problem was encountered during an X-15 flight in which the relatively low-gain basic SAS caused structural resonance of the horizontal stabilizers. It was obvious that because of its much larger gain values, the adaptive system would require an extremely deep notch filter to avoid the structural resonance. The high order of the notch filters required an extensive addition, filling all reserve space in the electronics assembly. Because the flight article was ready except for the notch filter, it was necessary to place the filter across the total gyro output, although only a small notch with correspondingly small phase lag was all that was needed for minimum-gain operation. This large additional phase lag of the notch filter raised another problem--limit cycles. A compromise had to be found, since, to reduce the effect of the limit cycles, phase lag had to be reduced. But, to do this, it was necessary to increase the gain at the structural frequencies. An acceptable compromise was found only after reducing the maximum gains allowed. The X-15 adaptive flight control system was now ready for flight.

OPERATIONAL EXPERIENCE

On the first flight, made in December 1961, some deficiencies were found that required correction. These deficiencies were associated with airframe structural dynamics or system interface, so that functionally the system did not have to be changed. By the fifth flight, all known or suspected deficiencies had been cleared, and the system was ready for acceptance demonstration. This was accomplished in July 1962 with a flight to 315,000 feet. The system met all requirements of the performance specifications to which it had been designed. During the 2 years and 4 months since the first flight, the system has been flown 27 times. There have been no failures affecting system performance or normal operation and only one component failure in flight--an enviable reliability record.

The question now arises concerning the quality of the system's performance. The principle governing the gain-changer operation has been discussed. An indication of how well the gain changer keeps the system gain at its critical value is given in figure 4. On this plot of system gain versus aircraft gain for the roll axis, the critical gain would correspond to a sloping line with $K_p L \delta_a \approx 80$ if the total system were linear and if the notch filter were removed. Because of hysteresis, the system is nonlinear so that the gain changer actually monitors the amplitude of limit cycle caused by the high gains and the hysteresis. This makes the "equilibrium" gain at the line shown for $K_p L \delta_a \approx 18$. It is obvious that the gain wanders to either side of this value. During entry from high altitude, the aircraft gain increases rapidly from a value near zero, which should cause the system gain to drop correspondingly from its maximum value. But, because of the hysteresis, the drop in system gain is delayed, as indicated by the large values of aircraft gain while the system gain remains at its maximum value.

A survey of all X-15 flights, including those in which the adaptive system was used, indicated that, for a large portion of the X-15 envelope, the adaptive system did not provide a clear-cut performance margin over the fixed-gain system. To investigate this further, a study of the controllability of the X-15 during entries from 360,000 feet was made using the simulator with the adaptive system. The pilot's task was concerned primarily with the pitch axis. He was to hold an angle of attack of 25° until the normal acceleration reached about $5g$, then hold $5g$ until level flight was attained. Sideslip and roll attitude were to be held as close to zero as possible. These entries (fig. 5) show very little difference in the pilot's ability to perform the maneuver, except for the entry at the lowest gain setting. In this entry, larger deviations occurred in all three controlled parameters. The pilot felt that excessive and continuous attention was required at the lower gain, whereas the moderate-gain and adaptive-gain entries were almost equally acceptable. These simulated entries compare well with an actual flight entry from 354,000 feet (right side of figure) for which the adaptive control system was used.

The results of this study are summarized in figure 6 in terms of pilot opinion of the entry control task for each of the systems investigated. From these data, it is apparent that successful entries can be accomplished with either fixed-gain or adaptive systems and that acceptable piloting performance and ratings are obtained with the moderate fixed-gain rate command system. It is interesting to note that the pilot ratings for actual flight are somewhat better than those for the simulator tests. Also, all pilots have stated that

controlling the airplane was easier in flight than on the simulator because of the additional visual and motion stimuli available in flight and the better mechanical condition of the airplane control system.

What this means in terms of controllability or handling qualities is indicated by the pilot opinions expressed for controllability throughout the X-15 flight envelope. Typical pilot ratings are shown in figure 7. To put these ratings in their proper perspective, all pilot ratings for various phases of many similar adaptive-system flights were averaged and are presented with similar averages for the fixed-gain system of the other X-15 airplanes. The pilot ratings with the adaptive system tend to remain fairly consistent throughout the flight in each axis. The pilot ratings for the fixed-gain systems indicated a significant deterioration when the pilot was required to maintain a high constant angle of attack at entry. The average rating for completing the entry with a fixed-gain system was relatively good. During the other portions of the flight, only slight improvement in the average pilot rating was noted for the adaptive system.

It is only fair to go back in history a bit with regard to a comparison of entries made with the fixed-gain SAS and the adaptive control system. When the altitude-buildup program started, the X-15 was equipped with a movable lower rudder which made the fin area at the bottom almost as large as that above the fuselage. The larger fin area was advantageous for directional stability but poor for control because of the huge dihedral effect it produced. Before we realized that we could do better without this fin, entries at angles of attack of 25° were very marginal with the fixed-gain SAS but were a "piece of cake" with the adaptive system. After the fin was removed and, consequently, the severity of the control problem reduced, there was less difference in the performance of the two systems.

On the basis of the advantages and disadvantages of the adaptive concept as set forth in 1955, an evaluation can be made of how well the system has operated and what it has actually achieved. Not all of the advantages discussed previously (page 1) have been realized:

The total development effort was not reduced by using an adaptive system for the X-15. It must be remembered, however, that part of this effort should be charged against developing the concept, since it is effort that did not have to be spent on subsequent applications.

It was not necessary to use data scheduling.

The response to control input is not exactly invariant but changes less for the adaptive system than its fixed-gain counterpart.

More, rather than less, analysis has been required because of the larger gain values.

The value of the aircraft gain does not need to be known as accurately.

The gain changer makes the airplane response less sensitive to configuration changes.

Removing the lower rudder has required minor changes in the system.

Some of the items which were expected to be disadvantages (page 2) also did not develop:

The system, with its dual redundant configuration, has proved to be an extremely reliable and fail-safe system.

No deterioration in actuator service life has been noticed.

Considerable attention had to be given to the resonance of the structural modes. Although this is of considerable concern in the adaptive concept, it is also a problem in the design of fixed-gain systems.

Pilot commands or random noise can also cause gain reduction at undesirable times.

In general, system performance has been most satisfactory and the reliability and fail safety which have been achieved in the system have certainly made the lengthy development time worthwhile.

ADAPTIVE CONTROL IN GENERAL

Thus far, the discussion has been limited to one particular adaptive flight control system in one particular application. What can be said in general about what adaptive control systems have to offer? One thing we cannot do is answer the question "Should you go adaptive," but we would like to offer a means of showing what can be gained by "going adaptive."

Consider the plot in figure 8 of system gain versus aircraft gain for the roll axis. Next, consider the quality of a roll-rate command system that could be designed using various combinations of system and aircraft gains. If control-system dynamics do not influence the pilot's assessment of the lateral handling qualities and the basic damping is negligible, the pilot ratings will be those shown in the figure. Now, consider the restraints that are imposed on the combination of system and aircraft gain by a variety of phenomena encountered in all high-gain flight-control-system applications. There is a maximum value of the gain as a result of structural feedback even after a filter of practical size is incorporated. This limit is represented by the horizontal line. There is a maximum value of the product of system gain and aircraft gain dictated by the limit cycles that can be tolerated, shown by the sloping line. In addition, there are more nebulous boundaries imposed by saturation and rate limiting, represented by the curved boundary in the upper left corner of the figure. Ideally, a control system would have the maximum gain allowed by these restrictions, with the corresponding pilot rating of the system.

Next, what is the range over which the aircraft gain changes as flight condition, configuration, and angle of attack are changed? To find the quality of a fixed-gain system, simply draw a horizontal line through the limit-cycle restriction at the point of maximum aircraft gain. The pilot ratings along this line represent the quality of control offered at the other values of aircraft gain. Pilot ratings for the best adaptive control system can also be obtained by following the upper limit.

If the aircraft gain simply does not change over a large range, or if at even the higher values of aircraft gain the system gain is limited by structural considerations, or if you are fortunate enough to be able to use very large products or system and aircraft gains, you do not need to go adaptive. If, on the other hand, you are limited primarily by the limit cycle or stability involving an aerodynamic gain and have an extreme range in aircraft gain, you have an argument for going adaptive.

CONCLUDING REMARKS

It was a challenging task to build a control system for the X-15 because of the airplane's extreme range of characteristics and modes of operation. In addition, the hysteresis and rate limiting of the basic control system are there to make trouble when high gains are used. In light of the difficulties posed by the X-15, the adaptive flight control system developed has been most successful. Although several problems were encountered during the development of the MH-96 adaptive system, and emphasis on them in this paper tends to paint a dark picture, these problems were solved on the ground before the first flight, except for some insignificant details which affected only the periphery functions of the MH-96 even during the early flights.

There is a saying that "a bird in hand is worth two in the bush." For adaptive flight control system concepts, we would put the ratio at about 10. An adaptive control system which has been successfully demonstrated in the X-15 is worth about 10 proposed new adaptive concepts which have not been exposed to the idiosyncrasies of control-system hardware.

SYMBOLS

b	span
$C_{l_{\delta_a}}$	rolling-moment coefficient due to aileron
I_x	moment of inertia about the X-axis
K_p	gain for the roll axis, deg per sec
L_{δ_a}	roll control power, per sec ²
q	dynamic pressure
S	area
α	angle of attack
δ	rudder deflection
ψ	angle of yaw

X-15 AIRPLANE

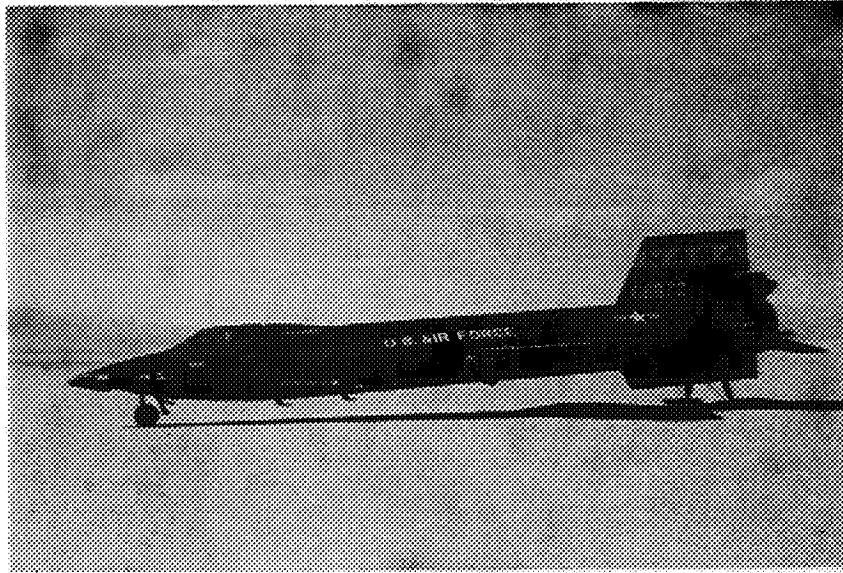


Figure 1

MH-96 ADAPTIVE CONTROL SYSTEM PITCH MODE

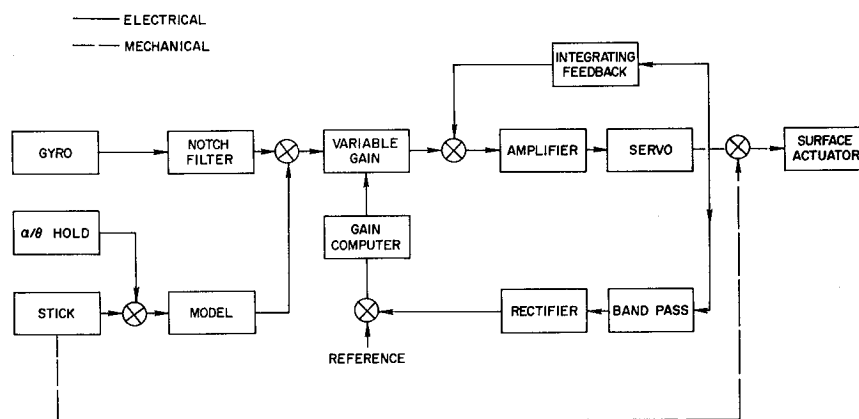


Figure 2

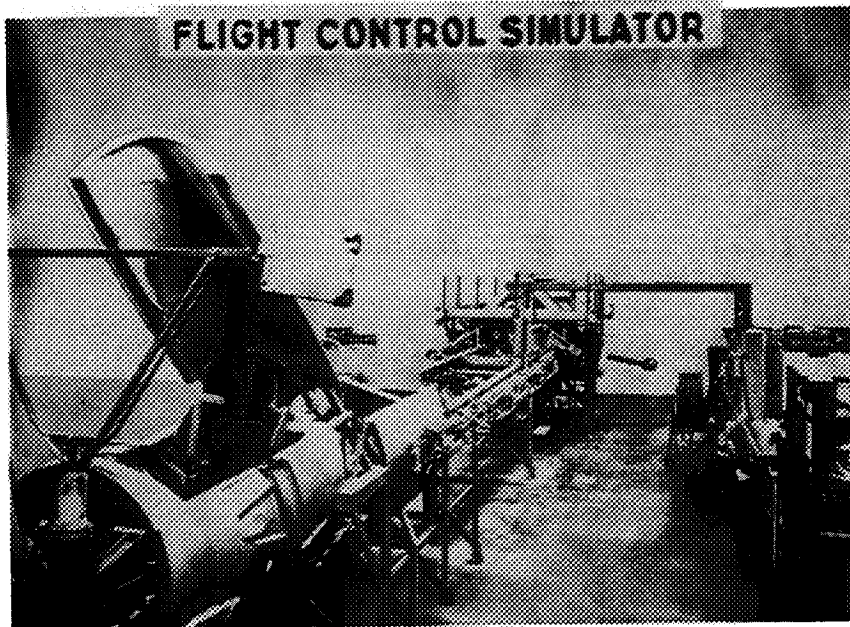


Figure 3

MH-96 SYSTEM GAIN-CHANGER OPERATION

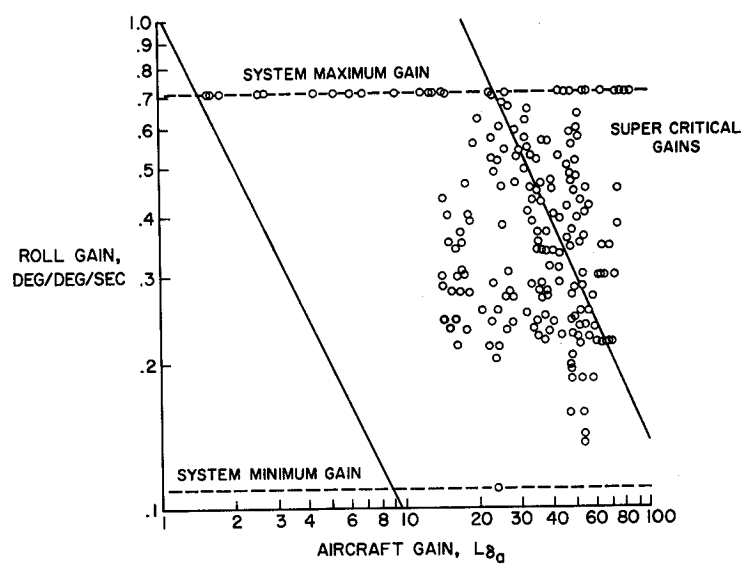


Figure 4

CONTROLLABILITY DURING X-15 ENTRIES

ENTRY FROM 360,000 FEET
RATE-COMMAND CONTROL

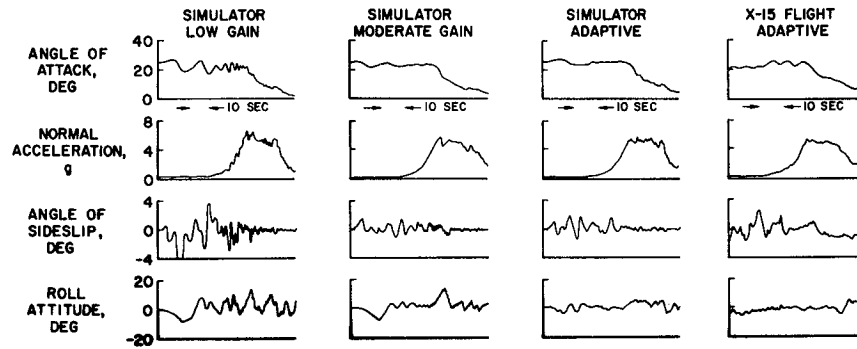


Figure 5

EFFECT OF DAMPER GAIN ON ENTRY CONTROL

ENTRY FROM 360,000 FEET
RATE-COMMAND CONTROLS

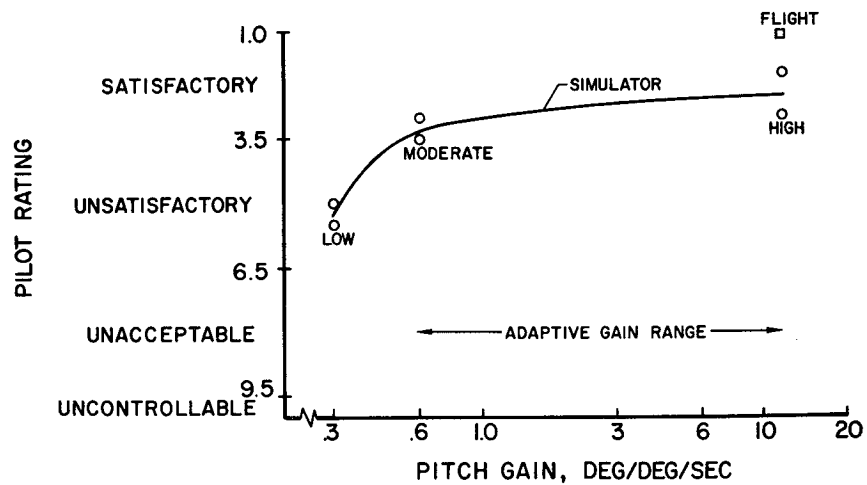


Figure 6

COMPARISON OF ADAPTIVE AND FIXED-GAIN SYSTEMS

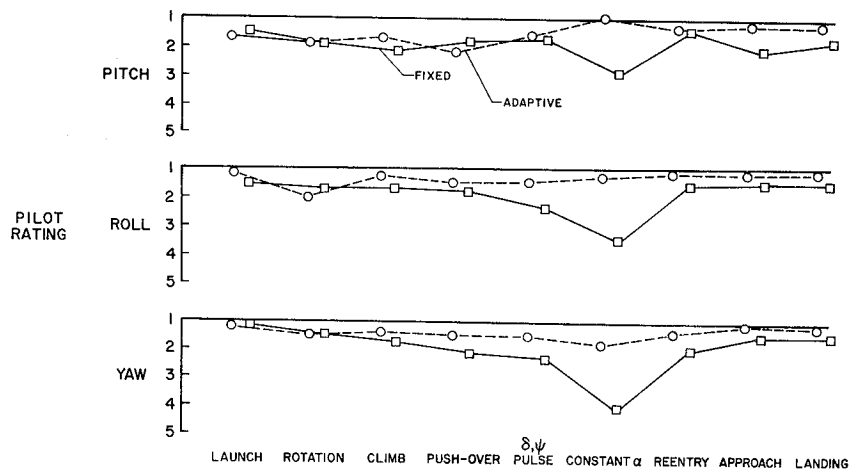


Figure 7

ROLL-CONTROL-SYSTEM DESIGN CONSIDERATIONS

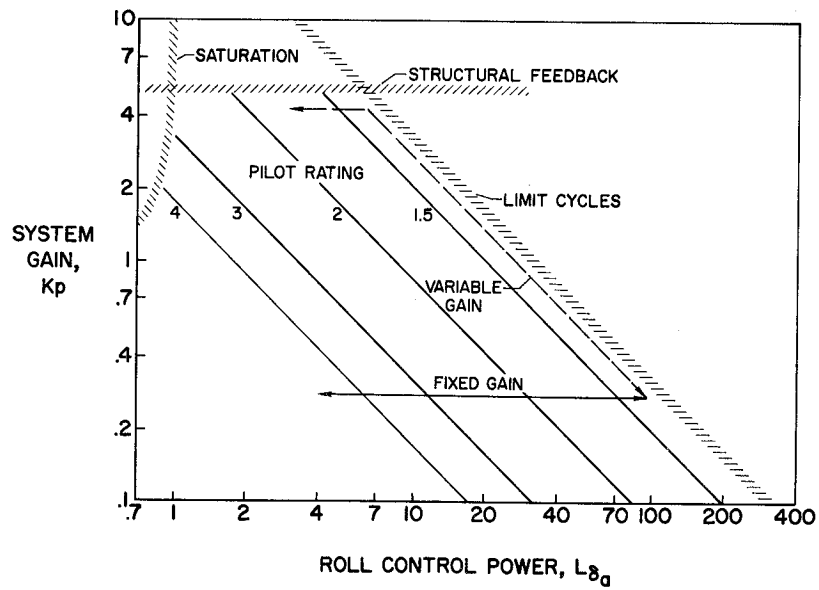


Figure 8